

“Observations on Atmospheric Electricity at the Kew Observatory.” By C. CHREE, Sc.D., Superintendent. Communicated by Professor G. CAREY FOSTER, F.R.S. Received May 11,—Read June 4, 1896.

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PART I.

The Measurement of Potential in Theory and Practice.

§ 1. An electrograph belonging to the Meteorological Office has been in operation at Kew Observatory, with interruptions, since 1861. The results obtained in the early years of its existence were dis-

cussed in 1868 by Professor Everett,* and the results obtained in 1880 were discussed in 1881 by my predecessor, Mr. Whipple.† Nearly two years ago, with the approval of the Kew Observatory Committee and the Meteorological Office, I commenced an investigation intended as preliminary to a consideration of the expediency of further publication of the electrograph records.

My first object was to find out whether definite quantitative measurements of potential could be derived from the electrograph curves. To aid in this investigation observations have been made at several spots near the Observatory with a portable electrometer, by White, of Glasgow, whose scale value was determined at University College by the kind assistance of Professor Carey Foster.

To render intelligible the bearing of these observations on the question, a brief description is required of the nature and position of the electrograph.‡ It consists essentially of a water-dropper and a quadrant electrometer. The water is held in a can, some 14 inches high and 15 inches in diameter, supported on three insulators of the Mascart pattern. From the can a tapering tube, resting on a fourth insulator, projects through a hole in a window facing the west. The end of the tube whence the water issues is $4\frac{1}{2}$ feet from the west wall of the Observatory, and 10 feet above the ground. The stream of water is regulated by two taps in the long tube. From the water-dropper an insulated wire passes to the needle of the quadrant electrometer. One pair of quadrants are kept at a given positive potential, the other pair at an equal negative potential, by means of a battery of 60 cells in series whose centre is to earth. The needle suspension carries a mirror, and light reflected from it produces a curve on photographic paper which is wound round a cylinder driven by clock-work. The position of the base line answering to the earth's potential—treated as zero—is obtained by putting the electrometer needle to earth, twice at least for each curve. Of late years the value of the curve ordinates, in volts, has been obtained from time to time by connecting the electrometer needle and one terminal of the portable electrometer, and varying their joint potential by means of an electrophorus. Simultaneous readings are taken of the curve ordinate and the portable electrometer.

If the ideal were attainable, the stream from the water-dropper should break up exactly at the end of the tube, and be always sufficiently copious to ensure the immediate picking up by the can and the electrometer needle of the potential existing in the air at the spot in question.

* 'Phil. Trans.' for 1868, p. 347.

† 'B. A. Report,' vol. 51, p. 443.

‡ (July 28.) Some alterations have been effected since the above was written

Interpretation of Electrograph Record.

§ 2. The first question is: supposing the apparatus perfect, does the electrograph supply information as to the potential anywhere except at the spot where the stream of water breaks into drops? To answer this question, one has to consider the influence of the environment, notably the proximity of a lofty building.

An investigation into this point was made ten years ago by Professor Exner, of Vienna, who found the equipotential surfaces near a building much deflected from horizontality. His results indicated apparently that for practical purposes the whole building might be regarded as possessing the earth's potential. Whilst it was anticipated that Exner's conclusions would hold good of Kew Observatory, it appeared prudent as a check to take observations with the portable electrometer, at a series of points in a vertical plane perpendicular to the west wall near the water-dropper. Observations were taken at heights of 3, 6, and 9 feet from the ground, which possesses, it may be explained, a slope away from the building. The base line, starting at the Observatory wall, terminated 57 feet away in a parallel wall 11 feet high, belonging to a much lower building. The observations were repeated on several days, but one example will suffice. The potential measurements are in volts, the distances from the Observatory wall in feet.

Table I.

Observations on November 6, 1894.

												Mean
Distance from wall.	3	6	12	18	24	30	36	42	48	54		potential.
Potential at height 3 feet..	4	6	18	38	48	46	34	24	16	6		26
„ 6 „ ..	8	18	40	58	88	84	76	68	52	22		56
„ 9 „ ..	—	28	44	76	102	120	108	68	36			78

In forming the means in the last column the results at 3 feet from the Observatory wall were omitted. The readings were uncorrected for variations of potential during the interval occupied by the observations.

So far as they go, the results are clearly confirmatory of Exner's. They show that the influence of a tall building in pulling down the potential extends to a considerable distance.

§ 3. The large dependence of the electrograph records on the immediate environment of the water jet complicates matters, but this need not prove a serious obstacle if the conditions allow us to regard the problem as one of statical electricity, in which influencing bodies are either stationary or at a distance. On this hypothesis, simultaneous potentials at any two neighbouring points would stand to one

another in a practically constant ratio, a function only of their geometrical coordinates.

If once this ratio were determined, one could deduce the potential at either point from that observed at the other. Regarding the spot where the water jet breaks up as one of these points, and selecting for the other a spot sufficiently distant from the building, one could deduce the *potential gradient* in the open, *i.e.*, the increase in voltage per unit of height above the ground. This point of view was apparently acted upon by Exner,* and by Elster and Geitel.† In both instances the existence of corroborative evidence is referred to, but I am not aware that particulars have been published. It would also appear that Exner and Elster and Geitel directed their attention mainly, if not exclusively, to clear quiet days.

There being no limitation to the use of the Kew electrograph, it appeared advisable not to restrict the investigations to days of a special kind, or to a particular season of the year.

Selection of Stations.

§ 4. It appeared desirable to compare the potential at more than two stations, so as to ensure a sufficient variety in the surroundings. I shall distinguish the stations selected by the letters A, B, C, D, E, F. Of these A is the flat top of a stone pillar, $3\frac{3}{4}$ feet high, in the Observatory garden, about 56 yards from the Observatory; it is surrounded by a frequently mown grass lawn. B is the top of a temporary wooden stand, $6\frac{1}{2}$ feet high, and only $3\frac{1}{2}$ feet from the west wall of the Observatory. C is the centre of a flat plank supported $3\frac{3}{4}$ feet above the ridge of a wooden building, situated about 100 feet to the south-west of the Observatory; it is 18 feet above the ground. D is on the south side of a stone parapet, $2\frac{1}{6}$ feet high, encircling the flat roof of the Observatory; it is 37 feet from the ground. E is the top of a camera stand, $5\frac{1}{2}$ feet above the Observatory roof, and 17 feet to the east of the central dome. F is the top of a stand on the roof—used for testing anemometers—level with the cups of the standard anemometer, from which it is distant about 17 feet to the north; it is 57 feet above the ground.

The observations were taken with the portable electrometer, and, as the burning end of the fuse was at a height of some 12 to 16 inches above the base of the electrometer, an addition of, say, $1\frac{1}{4}$ feet requires to be made to the altitudes of the several stations to get the height from the ground of the spot whose potential was measured.

A was the only station that could be regarded as practically uninfluenced by the neighbourhood of a building, and even in its case we

* 'Wien. Sitz.,' vol. 98, 1889.

† 'Wien. Sitz.,' vol. 101, p. 703, 1892.

have the influence of a massive stone pillar some $2\frac{1}{2}$ square feet in section. A calculation of the potential gradient which regards the observations at A as referring to a spot 60 inches above the ground in the open is certain to give an under-estimate. As it is impossible, however, to dispense with a support of some kind, and the presence of the observer is also a disturbing influence, no exact allowance can be made for this.

There have been four principal series of observations. In the first, occupying part of November and December, 1894, observations were taken, when practicable, once a day at stations A, B, C, D, and latterly at E also. In the second series, during part of March and April, 1895, observations were usually taken about 10.30 A.M. and 4.30 P.M. at each of the stations except F. The third series, during part of June and July, 1895, closely resembled the second; and the only material difference in the fourth was the substitution of station F for station D.

No observations were taken on Sundays or on Saturday afternoons. The observations were taken in a fixed order, and, thanks to the skill of the observer, Mr. E. G. Constable, a complete set of readings occupied only some seven or eight minutes. The time scale of the electrograph curves is far from open, and for this and other reasons I have judged it best not to attempt to reduce the readings with the portable electrometer to a common instant.

Comparison of Results at the different Stations.

§ 5. I have taken A as base station, and have found the ratios borne to the individual readings there by the corresponding readings at the other stations.

Let r_A , r_B represent corresponding readings at A and B, and let

$$r_{B/A} = \frac{1}{n} \Sigma (r_B/r_A),$$

where Σ denotes summation for a series of n observations. Then $r_{B/A}$ may be called the *mean value of the ratio* for the series of observations.

Also let us apply the term *percentage deviation of the ratio from its mean* to the quantity

$$\frac{\Sigma \{ (r_B/r_A) - r_{B/A} \}}{nr_{B/A}} \times 100,$$

in which the terms in the numerator are taken irrespective of sign.

Table II gives the extreme and mean values of the ratios during each series of observations, excluding three or four occasions when negative potentials were met with.

Table II.

Series of observations.	Number of observations.	r_B/r_A .			r_C/r_A .			r_D/r_A .		
		Max.	Min.	Mean.	Max.	Min.	Mean.	Max.	Min.	Mean.
I.	25	0.38	0.17	0.26	3.05	1.11	2.22	3.33	1.46	2.41
II.	45	0.54	0.16	0.29	2.32	1.40	1.78	4.52	1.46	2.28
III.	31	0.50	0.17	0.27	2.29	1.00	1.70	3.67	1.11	2.14
IV.	23	0.41	0.09	0.22	2.86	1.33	1.92	—	—	—

Series of observations.	Number of observations.	r_E/r_A .			r_F/r_A .		
		Max.	Min.	Mean.	Max.	Min.	Mean.
I.	25	4.95	2.46	3.12	—	—	—
II.	45	6.30	1.74	2.68	—	—	—
III.	31	4.33	1.11	2.51	—	—	—
IV.	23	4.73	2.05	2.87	8.34	2.71	4.53

In series I there were only twelve observations at station E. In series III the mean ratios for the higher stations are depressed by one abnormally low reading. The means in the different series vary, but the differences are too small to warrant any positive conclusion. They indeed suggest the possibility of the potentials at the higher stations being relatively somewhat higher in winter than in summer, but this may arise from a slight want of uniformity in the procedure followed at the different seasons.

The departures of the maxima and minima in Table II from the means are considerable, but the number of instances in which the departures from the mean are large is in reality small. This will be seen by reference to Table III, which gives the percentage deviations of the ratios from their means, treating each series of observations separately.

Table III.

Percentage Deviations from the Means.

Series of observations.	r_B/r_A .	r_C/r_A .	r_D/r_A .	r_E/r_A .	r_F/r_A .
I.	14	14	15	15	—
II.	19	10	19	21	—
III.	19	11	20	20	—
IV.	28	13	—	16	20

The irregularity in r_B/r_A may be due in part to the slightly unsteady character of the stand forming station B. The potentials at B were also much the lowest, so that errors of reading were there of most importance. At the highest station, F, the variations occurring in the potential sometimes made accurate measurements difficult.

§ 6. To give a clearer idea of the degree of uniformity shown by Table III, I give in Table IV the extreme and mean readings at the several stations, omitting, as in Table II, occasions of negative potential.

Table IV.

Readings in Volts at the several Stations.

Series of observations.	A.			B.			C.		
	Max.	Min.	Mean.	Max.	Min.	Mean.	Max.	Min.	Mean.
I.	264	104	158	66	22	40	552	120	352
II.	708	50	206	215	15	58	1320	81	364
III.	174	27	100	45	6	27	306	27	171
IV.	830	29	249	115	12	50	1452	52	476

Series of observations.	D.			E.			F.		
	Max.	Min.	Mean.	Max.	Min.	Mean.	Max.	Min.	Mean.
I.	648	152	385	776	264	524	—	—	—
II.	1464	122	455	1688	182	531	—	—	—
III.	354	30	210	498	30	246	—	—	—
IV.	—	—	—	1785	93	662	2362	122	1032

On one exceptional day the potential at A varied from -1200 to $+1290$ volts in less than forty minutes; at station F it varied from -2424 to over $+4000$ volts in about the same time.

Constancy of Ratios during the Day.

§ 7. Table V gives the mean values of the ratios for the forenoon and afternoon observations, treated separately, during those days when there were readings at both 10.30 A.M. and 4.30 P.M. The days available numbered 17, 10, and 9 respectively in the second, third, and fourth series of observations. The headings "A.M." and "P.M." distinguish the forenoon and afternoon observations.

In each case treated in table V the mean value of the potential for the forenoon was considerably higher than that for the afternoon. Thus, at station A the ratio of the forenoon to the afternoon mean potential—for those days only on which there were both forenoon

Table V.
Forenoon and Afternoon Ratios.

Series of observations.	$r_{B/A}$		$r_{C/A}$		$r_{D/A}$		$r_{E/A}$		$r_{F/A}$	
	A.M.	P.M.	A.M.	P.M.	A.M.	P.M.	A.M.	P.M.	A.M.	P.M.
II.	0.29	0.28	1.82	1.83	2.24	2.21	2.62	2.57	—	—
III.	0.24	0.33	1.75	1.52	2.16	1.87	2.57	2.17	—	—
IV.	0.22	0.23	1.96	1.88	—	—	2.76	2.87	3.99	4.46

and afternoon observations—was 1.37 in series II, 1.23 in series III, and 1.48 in series IV.

The difference between the mean potentials at the two hours on the specified days being so large, we may reasonably suppose that if any two other hours had been selected results would have been obtained showing a degree of accordance similar to that in Table V. The degree of accordance in the case of series II is truly remarkable, and in series IV, considering the smaller number of observations, it is but little inferior. If series III stood alone, we might suspect that in the afternoon the potential fell off more at the higher stations than at the lower, and this *may* of course be a true phenomenon of the season, midsummer, to which that series belongs.

Possible Dependence of Ratios on the Weather.

§ 8. It is conceivable that under one regular set of climatic conditions the potentials at the higher stations might relatively to the lower be either abnormally high or abnormally low. To test this point, the observations in each series have been divided into sets, according to the value of such a ratio as r_E/r_A . Attention has been confined to series II, III, and IV, as in series I the times of observation were less regular; but the forenoon and afternoon observations in series II and III have been considered separately.

Supposing the number of measures of, say, r_E/r_A available in any one instance to be $2n$ or $2n+1$, the n cases in which the ratio is largest form one set, the n cases in which it is smallest the other. For each of these sets the corresponding mean values of certain meteorological elements have been calculated, the data for the individual times of observation being derived from the self-recording instruments employed in the Observatory. The figures as to aqueous vapour and humidity have been deduced from the thermograms, with the aid of a modification of Glaisher's table, compiled by the Meteorological Office.

By "sunshine in hours" is meant the number of hours of sunshine measured by the Campbell-Stokes recorder up to the time of observation. The data under this head have been limited to the most sunny series of observations, viz., II and III.

The results are exhibited in Table VI, which shows also the maxima and minima values of the meteorological elements observed during the several sets of n observations.

There is in Table VI no uniform and conspicuous connexion between the value of $r_{E/A}$, or $r_{F/A}$, and the corresponding value of any one of the meteorological elements considered. In the case alike of barometric pressure and temperature the second mean—answering to the n lowest values of $r_{E/A}$ or $r_{F/A}$ —is higher than the first in five instances out of six. The differences between the two means are generally, however, so small that the phenomenon may be purely accidental. In the afternoon observations of series II there is a somewhat conspicuous association of a low value in $r_{E/A}$ with a high value of previous sunshine; but in series III there is no trace of such a phenomenon.

The question whether there may not be certain *occasional* types of weather, whose influence is masked in such a table as VI, which are associated with either a high or a low value of the ratio $r_{E/A}$, remains, I think, open. Evidence is in my hands which leads me to believe that during a low ground fog the potential gradient as a rule is decidedly higher near the ground where the fog is thick than higher up where the fog is slight.

Summary of Results at Different Stations.

§ 9. The conclusion I am disposed to draw, though I regard it as only a probability, is that such general phenomena as diurnal or annual variation of potential near the ground in the open may be deduced with fair accuracy by applying a constant factor to the records of a portable electrometer, employed regularly at a fixed point on the Observatory roof or near its walls. It must be remembered, however, that all six stations were comparatively close together, and that the equipotential surface passing through the highest station would be in the open perhaps only 14 or 15 feet above the ground. There is thus no evidence to warrant the deduction of conclusions for a spot a mile or two away or a few hundred feet above the ground.

On the trustworthiness of individual results deduced by means of a constant factor, one would not, after inspecting Tables II and III, be disposed to place much reliance. This question can hardly, however, be settled satisfactorily unless one have apparatus for taking the observations at the different stations absolutely simultaneously. The largest departures from the means in Tables II and III are

Table VI.

Observations.		Ratio treated.	Value of n .	Mean value of ratio.		Aqueous vapour, grams per cubic metre.			Barometer in inches.			Temperature, Fahrenheit.			Wind velocity, miles per hour.			Sunshine in hours.			
Series.	Time.			n	n	Max.	Min.	Mean.	Max.	Min.	Mean.	Max.	Min.	Mean.	Max.	Min.	Mean.	Max.	Min.	Mean.	
II.	Forenoon	$r_{E/A}$	12	{	3.09	—	9.03	4.67	6.70	30.20	28.86	29.72	53.1	41.6	47.3	40	4	14	3.4	0	1.0
"	Afternoon	"	10	{	3.42	—	8.54	5.25	6.66	30.37	29.27	29.97	56.4	39.1	47.6	21	0	8	4.2	0	1.1
III.	Forenoon	"	8	{	3.09	—	9.19	4.69	6.74	30.17	28.92	29.64	61.6	43.0	49.9	27	1	12½	9.4	0	1.9
"	Afternoon	"	7	{	2.61	—	8.95	5.22	6.50	30.35	29.08	29.89	61.0	43.2	52.6	23	4	15	10.2	0.7	5.2
IV.	Forenoon and afternoon	"	11	{	3.35	—	12.13	8.36	9.68	30.41	29.68	30.05	72.9	57.5	67.7	13	5	9	5.5	0	2.7
"	"	"	11	{	5.46	—	12.62	6.33	9.28	30.38	29.56	29.99	68.8	63.0	65.5	24	3	10	5.7	0	2.6
"	"	"	11	{	3.61	—	10.81	8.68	9.87	30.27	29.62	29.88	79.1	65.1	70.9	22	4	14	11.6	1.2	6.9
"	"	"	11	{	3.61	—	13.26	6.90	9.95	30.40	29.69	30.07	76.2	67.2	71.7	27	4	13	11.1	1.3	6.3
"	"	"	11	{	3.61	—	7.76	4.41	5.54	30.52	29.48	29.95	49.7	35.4	42.1	18	1	8	—	—	—
"	"	"	11	{	3.61	—	9.07	4.02	6.81	30.47	29.57	30.07	57.0	34.2	46.3	29	0	9	—	—	—
"	"	"	11	{	3.61	—	9.07	4.41	5.92	30.52	29.54	29.96	57.0	35.4	43.7	29	1	9	—	—	—
"	"	"	11	{	3.61	—	8.16	4.02	6.26	30.47	29.48	30.00	49.0	34.2	44.2	11	0	7	—	—	—

doubtless due in great part to changes occurring whilst the observations were in progress.

Possible Influence of Pattern of Instrument.

§ 10. The conclusions in the previous paragraph refer as yet only to the portable electrometer. They can be extended to the electrograph records only if we are able to show that a fairly uniform ratio exists between the potential obtained with the water-dropper at a fixed station and that obtained with the portable electrometer at one or other of the stations A to E.

The position of the water-dropper was maintained undisturbed, barring accidents, throughout the observations. It thus suffices to compare the curve readings with the corresponding ones with the portable electrometer at station A. The curves were accordingly measured at the mean times of each set of observations. The ratios of the individual readings to those at station A were calculated, and results obtained analogous to those in Table II. It will suffice for our present object to consider the results analogous to those in Table III.

Table VII.

Percentage Deviations from the Means (Electrograph/Portable).

	Series of observations.			
	I.	II.	III.	IV.
Percentage deviations	28	30	35	28

The spot where the jet breaks up resembles B more closely than any other station, and shares its low potential. Further, the electrograph curves are read to the nearest 5 volts only, so that uncertainties in the reading are even more important than with the portable, read to the nearest 1 or 2 volts, at station B. Thus, the results in Table VII are, at least, not conspicuously worse than those in Table III. As a matter of fact, the results in Table VII were, I believe, somewhat prejudiced by a variation in the water jet throughout the day (see § 11). Supposing this defect removed, the evidence points to the conclusion that the diurnal, and possibly the annual, variations got out with the water-dropper situated in the Observatory, and the portable electrometer at station A, may be expected to be in good accord, assuming the conditions under which each instrument works to be maintained uniform.

Attention was also directed to the possibility of the two different patterns of instrument being differently affected by the same climatic conditions. Each series of observations—the forenoon and afternoon observations of series II and III being treated separately—was

arranged in descending order of some one meteorological element. Suppose there to be $2n$ or $2n+1$ observations in the series (or half series); the mean values of the ratios borne by the electrograph readings to the corresponding ones with the portable electrometer at station A were calculated for the first n and the last n instances separately. Supposing r_1 , r_2 , and r to denote the mean ratios for the first n , the last n , and the whole $2n$ (or $2n+1$) observations, then

$$\frac{1}{2}\{(r_1-r_2)/r\} \times 100$$

may be regarded as the average percentage deviation of the two groups from the mean. Table VIII gives the value of this quantity in the case of the three meteorological elements from which a differential effect was most feared.

Table VIII.

Value of $\frac{1}{2}\{(r_1-r_2)/r\} \times 100$.

Series of observations.	Times of observations.	Meteorological element considered.		
		Vapour density.	Sunshine.	Wind velocity.
I	Day	-15	..	- 8
II	Forenoon	-12	+ 8	+ 8
	Afternoon	+ 1	+ 4	+12
III	Forenoon	-20	+14	+22
	Afternoon	-15	+15	-16
IV	Day	-15	..	< 0½

A plus sign denotes that when the meteorological element in question was above its mean the water-dropper was more than usually effective, relative to the portable electrometer; a minus sign implies the contrary.

The evidence in the case of wind velocity is so contradictory that we can safely assume that no uniform differential action exists.

In the case of the two other elements the evidence is more consistent, and it is possible that a small differential action may exist. It looks as if much moisture, when not counterbalanced by a contrary action of sunshine, tends slightly to pull down the reading of the water-dropper relatively to that of the portable electrometer. The phenomenon, supposing it to exist, might be ascribed to a loss of efficiency in a water jet when the vapour in the air increases, and a similar loss in a flame collector during bright sunshine. But an influence at least as likely is that of moisture, during damp weather, on the insulation of the electrograph.

Defects in Water-dropper and Portable Electrometer.

§ 11. Both instruments aim at communicating the potential at a fixed point in the air to an insulated conductor by detaching from a mass in electrical connexion with the conductor a continuous succession of small elements. It is at least doubtful whether either instrument can ever fully accomplish its object. If the object were so far accomplished that a constant fraction of the true potential were recorded, the deficiency of this fraction from unity would hardly be of primary importance in dealing with diurnal or annual variation; but if the fraction has itself a diurnal or secular variation it is a very different matter.

In the water-dropper a uniform state of insulation of the water-can, electrometer needle, and connecting wire is not easy. Absolute insulation, when a voltage runs up to hundreds, is a somewhat ideal state of perfection. When the insulation is indifferent, the recorded may fall far below the true potential. The water jet, so to speak, is running up the potential, leakage from the can, wire, &c., running it down. The resultant effect depends on a variety of things, *e.g.*, the rate at which the air potential is changing and the supply of water particles. Unless the potential is unusually steady, and the insulation exceptionally good, one may expect higher potential records with a copious jet than with a restricted one.

In the portable electrometer there is similarly some ground for expecting the potential recorded to be influenced by the rate of combustion of the fuse.

The uniformity of the disintegrating mass may also be of importance. With a water-dropper there ought not to be much uncertainty on this ground, but as electrometer fuses are articles of commerce uniformity in their material and condition is less easily ensured.

There is a final source of uncertainty common to the two instruments as commonly used. With the water-dropper the spot where the jet breaks up is apt to be slightly influenced by variations in the water pressure. When the issuing jet makes as usual an angle with the wall of a building, the consequences, as appears from Table II, are likely to be appreciable. It was a recognition of this fact that led to the taking of the observations with the portable electrometer at two nearly fixed hours, the afternoon one when the can was nearly full, the forenoon one when it was about half empty.

The corresponding defect with the portable electrometer is the burning down of the fuse. When the fuse is used in a vertical position, the height of the spot whose potential is being measured diminishes as the fuse burns, and with the height the potential falls off.

No direct comparison of the readings of the two instruments at one

and the same spot was attempted during the observations, as it seemed undesirable to interrupt the continuity of the electrograph records. All that § 10 shows is that during any one series of observations the fractions of the true potential picked up by the two instruments stood to one another in a fairly constant ratio. The presumption, certainly, is that neither fraction altered much throughout the few weeks covered by any one of the four series of observations.

It is, however, I regret to say, perfectly certain, from the data on which § 10 is based, that one at least of the two instruments varied very considerably in the course of a year and possessed an appreciable diurnal variation.

§ 12. On the discovery of these defects it became not only justifiable but necessary to subject the water-dropper itself to direct experiments. These have led to my proposing certain alterations which are now in process of execution. They aim at bringing the water-can and electrometer close together, and at maintaining a more uniform water pressure than heretofore.

It appears also desirable to check the working of the apparatus in some way involving the arrival at exact numerical results. The following operations A, B, C will, it is hoped, prove sufficient. The operation C need not be performed so frequently as A or B.

A. Charge the quadrant electrometer needle to a high potential, and observe the rate of leakage over a fixed range by timing the motion of the spot of light across a scale with—

- (1) the wire connexion to the water-can complete, but the jet not flowing ;
- (2) the wire connexion broken at the can ;
- (3) the wire connexion broken at the electrometer.

B. As a substitute, or as subsidiary to A. Connect a portable electrometer to the water-can, and, with the jet flowing, observe the potential recorded by the portable, when—

- (1) the can is connected as usual to the quadrant electrometer ;
- (2) the connexion is broken at the quadrant electrometer ;
- (3) the connexion is broken at the can.

C. Take a sufficient number of observations at a fixed station outside with a portable electrometer, at or near two fixed hours a day, so chosen that at one hour the can is almost full, whilst at the other it is at least half empty.

The use to be made of the results is obvious.

I should also recommend any one using a portable electrometer to test its scale value from time to time by comparison with an absolute electrometer or a large battery of constant cells. It is well to lay in a new stock of fuses before exhausting one's supply, and to compare the old and new fuses by taking observations in rapid succession with samples of the two at a fixed station.

PART II.

Application of Results to Theories of Atmospheric Electricity.

§ 13. It seemed desirable to consider what bearing the special experiments might have on the general facts and theories of atmospheric electricity. In this investigation special attention has been given to the possible influence of aqueous vapour on electrical potential, on account of the important researches of Exner, and of Elster and Geitel.

Theories of Exner and of Elster and Geitel.

§ 14. Exner has advanced the view that the potential gradient in the open, dV/dn in his notation, and the density q_0 of aqueous vapour simultaneously present in the atmosphere, are connected by a formula

$$dV/dn = \text{constant} \div (1 + kq_0),$$

where k is apparently a constant, the same at all places and at all seasons of the year. Exner, I believe, limited his observations, and presumably the application of the formula, to days comparatively quiet and free from clouds. To test the formula he arranged his observations in groups, according to the amount of vapour present, and compared the mean vapour density—measured in grams per cubic metre—with the mean potential gradient, measured in volts per metre of height above the ground. In the ‘Wien. Sitz.,’ Bd. 99, p. 618, he gives a table including results from Vienna, Wolfenbüttel, St. Gilgen, and India, in which the vapour densities vary from 1.7 to 23.5. The table unquestionably shows a diminishing mean potential gradient accompanying an increasing mean vapour density. For values of q_0 from 12.4 and upwards, however,—including all the Indian and most of the St. Gilgen observations—the change in dV/dn is somewhat small and irregular. An earlier, and somewhat similar, but less extensive table by Exner will be found on p. 434 of ‘Wien. Sitz.,’ Bd. 96.

For information as to Elster and Geitel’s work I am mainly indebted to a long paper by them in the ‘Wien. Sitz.,’ Bd. 101, p. 703, 1892. During 1888–91 they took an extensive series of observations on quiet days at Wolfenbüttel. If I follow their explanations, they took eye observations some ten times a day with an electrometer, in which flame from a lamp acts as collector, and deduced the mean value of the potential gradient dV/dn for the day. They compare these potential gradients grouped according to the value of the vapour density with Exner’s formula, taken to be

$$(dV/dn) \text{ (in volts per metre)} = 1410/(1 + 1.15q_0),$$

where q_0 is measured as above in grams per metre. They give an abstract of the results on their p. 742, in the shape of a table which I reproduce.

Elster and Geitel's Table III (*loc. cit.*, p. 742).

$q_0 =$	1·6	1·9	2·5	3·7	4·6	5·6	6·5	7·6	8·4	9·4	10·6	13·5
dV/dn (observed) =	502	430	400	318	252	137	184	148	112	115	118	121
„ (calculated) =	496	442	364	268	224	189	166	145	133	119	107	85

It would appear that Elster and Geitel, like Exner, found large departures from the mean dV/dn of a group amongst its individual members.

§ 15. Elster and Geitel next proceed to investigate a possible connexion between the potential gradient and the intensity of that species of solar radiation which dissipates a negative charge on an insulated sphere of polished zinc. If I understand them rightly, they measured the mid-day intensity J of this radiation, and compared the potential gradient with several formulæ in which the variable was either J or Jf , where f is a “Beleuchtungsfactor,” equal apparently to (possible hours of sunshine) / 12. Taking a formula $dV/dn = 110 + 360a^{-J}$, where $\log a = 0\cdot0100$, they give the following comparison of the results of observation and theory :—

$J =$	2·9	5·8	9·1	21·4	58·8	77·1	113·7	121·9	181·3	194·5	268·4
dV/dn (observed) =	447	430	368	325	198	181	138	126	120	106	102
„ (calculated) =	447	425	402	330	203	171	136	132	116	114	111

The agreement seems better than in the case of Exner's formula, and Elster and Geitel seem strongly inclined to regard ultra-violet radiation as the direct cause of variations of potential on normal quiet clear days. They consider apparently that there are only two defective links in the chain of evidence, viz. :—

- (1) absolute proof that the earth is electrified negatively ;
- (2) proof that there is a sufficient supply at the earth's surface of materials susceptible to the influence of ultra-violet light.

There are, of course, numerous other theories of atmospheric electricity, but none, so far as I know, admits of numerical comparison with observation.

Method of Treating Kew Observations.

§ 16. In discussing the Kew observations I have in general employed a method differing from the grouping system of Exner and Elster and Geitel, and have also treated the several series separately. It is clear from data mentioned by Exner that the potential gradients for individual members of his groups varied in some instances largely from the mean; and it was soon obvious that the same phenomenon would present itself if any similar treatment were applied to the Kew results. This is undesirable, because by varying the limits of the groups the accordance of the results with a particular formula may be much improved, or the reverse. However impartially, so to speak, the lines may be drawn, there is undeniably a risk of introducing some fictitious result; and no critic can feel that he is in a position to judge of the results until he has examined for himself the circumstances of the grouping, a labour he naturally shrinks from. Again a wide range of such an element as vapour density can be obtained at a particular place only by combining results from all seasons of the year. This brings us to a second question. Electrical potential gradient has like vapour density, sunshine, and temperature, a large annual variation, only, unlike these elements, it is highest in winter. It is thus obvious that when observations from all seasons of the year are treated promiscuously, there is almost sure to be a marked association of high potential with low vapour density, little sunshine, and low temperature; and a judiciously selected formula which makes potential diminish as any one of these elements increases is certain to show some approach to agreement with observation. It is thus desirable to compare together observations from a limited portion of a year, or, even better, from the same season of a series of years. Similar considerations show an advantage in treating separately results from different hours of the day. The isolation of particular seasons and hours has the disadvantage of reducing the number of observations compared together. This is, however, partly compensated for by the greater homogeneity of the material. It also enables one in some cases to compare readily the mean potential gradients which answer at different seasons or hours to like values of some one meteorological element (see § 23).

Anticipation of some Criticisms.

§ 17. The Kew observations were not limited to quiet, comparatively cloudless days, in the same way as the observations of Exner and Elster and Geitel seem to have been. It may thus not unlikely be supposed that the Kew results are affected by a variety of disturbing causes, which diminish their intrinsic value and their suit-

ability for comparison with other results free from these extraneous effects.

As to intrinsic value, there are, at least in England, seasons of the year when a nearly cloudless day is exceptional. For instance, during November and December, 1894, in ten days out of eighteen, on which observations were taken a little before noon, no bright sunshine was recorded up to the hour of observation. At such a season, if one confined one's attention to nearly cloudless days, hardly any data would be obtained, and they might not unreasonably be regarded as abnormal.

As to the disturbing action of clouds, this is no doubt in some cases very large; but with clouds of this character the influence may be considerable when they cover only a small fraction of the sky, and probably, in some cases, even when they are below the horizon. Thus on one occasion at Kew, when part of the sky was covered by a thundercloud—so distant that only one or two faint lightning flashes were detected—sudden changes of potential of thousands of volts from negative to positive and back again were observed on the roof, whilst the sun shone at intervals. The sudden alternations of potential doubtless accompanied flashes of lightning, but no rain was falling anywhere near, and possibly an observer a few miles away might have regarded the day as an ideal quiet one. Again, there are other forms of clouds whose influence seems not unlikely to be much less than that of invisible vapour in motion nearer the ground. The mere interception of sunlight by cirrus clouds or detached masses of cumulus, if we may judge from some few experiments at Kew, has little if any effect.

It should also be borne in mind that wind velocity and amount of cloud must both have varied appreciably from day to day, and even throughout the individual days of Exner's experiments. Some one—I forget who—defined a "quiet" day as one in which the flame of Exner's electrometer was not blown out. All the days of the Kew observations satisfied, of course, this definition, if one is allowed to substitute the portable electrometer for Exner's, yet on one occasion the anemometer was recording a mean velocity of forty miles an hour.

If aqueous vapour, as Exner supposes, is the sole, or even the dominant, agent in producing changes in potential, its activity can hardly be confined to days when there is little cloud, and the wind is low.

§ 18. As regards Elster and Geitel's theory, the data available for criticism are, I admit, defective, inasmuch as no measurements are taken at Kew of the dissipative effect of sunlight on negative electricity. I presume, however, that bright sunshine—such as the Campbell-Stokes instrument records—always possesses this power,

though doubtless in very variable degrees at different seasons. Solar radiation occurring after an observation is taken, clearly cannot affect it. Thus the data got out as to the amount of bright sunshine recorded prior to the observations must, I think, bear fairly directly on Elster and Geitel's theory. If it be true, the potential gradient must, I think, fall conspicuously as the number of hours of previous sunshine increases.

§ 19. An objection of a different kind is the proximity of the Kew Observatory to London. This objection has already been urged against Greenwich by investigators* whose theories do not harmonise with the results obtained there. A weekly period exists, they say, in the Greenwich electrograph curves, and this, they assume, can arise only from a weekly fluctuation in the amount of smoke, due to our insular habits of keeping Sunday. If, for a moment, we suppose the phenomenon and explanation both true—a pretty large assumption—there seems a wide step to the conclusion that results so affected are useless. I do not myself see that they need lead to erroneous conclusions, unless one is dealing with a cycle whose period is seven days, or a multiple thereof, which a lunation, for instance, is not.

In the present instance I would point out that the prevailing winds during each one of the series of observations were from directions included between N.N.W. and S., and that as Kew Observatory is some miles to the *west* of London, while the manufacturing districts are mainly in the east, it is difficult to see how London smoke could affect the results. The Observatory, I should add, is situated in a large open park to the immediate west of the extensive Kew Gardens.

Even if the prevailing winds had been easterly, I question whether smoke would have exerted an appreciable influence. The analysis above mentioned of the electrograph results for 1880, by the late Mr. Whipple, seems to show that if any relation existed then between electric potential and wind direction, it varied with the season of the year; this would hardly have occurred if smoke present in east winds had an appreciable effect.

Tables of Results.

§ 20. In discussing the observations, I have decided to commence by incorporating the actual details in a series of tables. This will enable any one to judge for himself whether the conclusions finally arrived at are in accordance with the facts. The first eight tables give full particulars of the results. The arrangement is not

* See pp. 42—43 of offprint of paper by Ekholm and Arrhenius in 'Bihang till k. Svenska Vet.-Akad. Handlingar,' Band 19 Afd. 1, No. 8, Stockholm, 1894.

Table IX.

Results for November—December, 1894, forenoon, about 11.50 A.M.

Volts observed at stations					Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	D	E						
264	66	464	640	—	7.33	85	0	48.0	1.11	10
232	66	552	648	776	7.69	96	0	45.5	1.04	10
208	36	496	612	670	5.66	92	0.2	38.6	1.38	13
198	48	408	494	620	5.52	79	2.8	42.0	1.60	11
196	38	508	516	728	9.30	99	0	50.2	1.09	1
192	46	400	452	568	6.12	92	0	40.5	1.06	10
192	40	408	416	516	3.97	76	0.3	34.0	0.65	15
188	44	464	540	—	8.23	88	0	50.0	1.09	10
168	46	382	362	—	5.29	92	0	36.5	1.00	4
160	42	322	376	476	4.96	67	2.8	43.1	0.98	19
152	58	362	280	—	5.76	74	2.8	44.5	1.46	14
148	32	452	428	—	7.69	96	0	45.5	0.81	3
124	32	264	292	368	5.45	67	2.5	45.9	1.02	29
124	26	290	250	322	4.52	66	2.3	41.5	0.84	33
116	30	320	340	574	7.62	82	0	50.0	1.15	22
106	32	198	240	264	5.63	72	1.8	44.8	0.49	20
104	35	180	152	—	5.26	75	0	42.0	1.35	7
84	22	230	280	—	5.95	88	0	41.0	0.85	6
Means ..	164	41	372	406	6.22	83	0.86	43.5	30.03	13.2

Table X.
Results for November—December, 1894, afternoon (times various).

Volts observed at stations (A B C D E)	Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
192 42 424 452 —	6.60	84	1.2	45.0	0.91	8
164 44 416 364 404	5.47	67	2.2	46.2	0.53	18
160 58 404 530 —	4.88	94	0	33.5	0.70	2
148 40 276 308 —	7.14	87	0.2	46.6	1.09	12
114 28 270 212 —	6.22	79	0.5	45.0	1.01	20
108 28 120 254 —	6.47	92	0	42.0	1.26	0
104 32 182 195 —	5.03	89	0	35.9	1.48	3
Means.. 141 39 299 331	5.97	85	0.59	42.0	30.00	9

Table XI.
Results for March—April, 1895, forenoon, about 10.30 A.M.

Volts observed at stations					Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	D	E						
708	183	1320	1464	1688	5.50	87	1.0	39.1	1.30	3
580	215	812	847	1073	5.55	87	1.0	39.6	0.66	1
415	75	696	702	806	5.25	67	0	44.9	0.64	10
406	96	687	818	908	6.73	78	0.4	47.9	1.34	0
400	101	690	847	986	5.84	67	2.3	48.0	1.19	4
304	67	560	600	664	7.89	82	1.3	50.8	0.92	11
275	73	499	537	589	6.38	70	0.5	49.5	1.37	8
260	67	502	542	580	8.54	73	0.3	56.4	1.00	5
203	58	412	455	563	4.67	71	1.3	40.1	0.97	22
186	52	302	377	441	6.49	84	0	44.9	1.02	9
186	58	348	314	345	5.73	88	0	40.2	0.93	6
180	35	412	604	687	7.66	96	0	45.6	0.10	4
168	55	248	522	598	7.27	81	0.2	48.8	0.80	6
166	29	288	296	319	6.12	68	3.3	48.8	0.27	21
165	46	270	472	551	7.85	76	3.4	53.1	0.94	6
160	38	258	293	348	8.36	74	0.8	55.3	0.91	13
133	35	232	336	413	9.03	94	0	50.9	0.93	9
122	38	238	280	293	4.81	72	0.9	41.6	1.10	10
108	49	226	242	299	8.39	83	0	52.2	0.82	14
104	26	174	214	260	6.48	78	2.0	47.0	1.86	40
104	32	174	215	226	6.35	60	4.2	53.7	1.28	5
67	29	131	160	182	6.06	73	0	47.0	0.56	24
52	15	81	122	191	5.82	75	1.3	44.3	1.20	10
50	27	116	139	197	6.54	72	0.3	49.0	0.21	20
Means..	229	62½	403	475	550	77	1.02	47.4	29.85	10.9

Table XII.

Results for March—April, 1895, afternoon, about 4.30 p.m.

Volts observed at stations						Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	D	E							
395	145	630	1307	1530		5.61	70	2.0	46.0	0.72	18
377	90	568	1125	1351		5.93	82	1.6	43.0	0.17	13
290	70	493	595	696		6.42	69	0.7	50.0	1.35	4
264	70	499	512	621		5.63	62	2.0	49.3	0.64	13
209	64	307	368	452		6.88	59	8.3	56.5	1.08	9
177	47	394	435	485		4.69	64	1.2	43.2	1.17	6
168	64	302	348	418		6.74	65	6.8	53.1	1.27	7
168	55	328	531	580		7.70	56	9.4	61.6	0.91	6
168	41	270	290	345		5.81	63	3.7	49.4	0.43	20
151	41	313	365	397		7.67	70	2.5	54.8	0.80	23
151	44	281	293	338		8.95	66	6.0	61.0	0.92	19
149	52	261	247	339		5.22	71	4.8	43.2	1.06	11
145	52	258	383	420		7.85	76	0.3	52.9	0.89	8
130	32	240	299	371		9.19	69	1.0	60.4	0.86	11
122	27	218	212	218		6.11	65	6.8	50.3	0.08	28
122	32	261	296	348		6.32	78	1.1	46.2	0.89	1
116	35	261	313	345		5.17	60	2.4	48.0	1.92	27
110	32	168	200	217		5.61	47	10.2	57.9	1.26	14
99	41	174	447	624		6.21	79	0	45.4	0.86	14
96	15	197	212	255		8.72	86	0	52.2	0.04	21
Means ..	180	52	321	439	517½	6.62	68	3.54	51.2	29.77	13.6

Table XIII.

Results for June—July, 1895, forenoon, about 10.30 A.M.

Volts observed at stations					Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	D	E						
174	39	306	354	405	9.11	57	0.5	65.7	0.87	3
141	36	204	279	357	6.33	38	5.1	66.8	1.38	5
117	27	180	186	213	12.44	78	0	65.7	1.33	8
114	30	207	255	300	9.52	50	4.3	70.6	1.02	13
105	21	168	204	246	12.62	81	0	65.2	0.68	7
105	18	204	234	276	8.58	45	5.5	71.0	1.11	7
105	30	189	225	279	12.01	66	0.3	69.5	1.41	6
102	36	234	291	351	8.58	60	1.5	62.8	1.18	5
99	27	153	177	186	8.50	59	1.2	63.1	0.56	24
99	27	180	264	291	9.54	78	0	57.5	0.68	7
90	24	180	180	216	7.88	48	5.7	66.0	1.25	11
90	15	183	207	264	12.13	60	3.9	72.9	1.14	6
87	18	150	225	270	8.76	47	2.1	66.6	0.93	13
84	24	147	150	168	7.96	55	4.0	63.0	0.95	9
81	15	129	153	201	9.38	53	4.5	68.8	0.91	16
36	9	69	132	156	8.36	44	4.0	71.0	0.91	13
Means..	102	25	180	220	261	57	2.66	66.6	30.02	9.6

Table XIV.

Results for June—July, 1896, afternoon, about 4.30 P.M.

Volts observed at stations						Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	D	E							
162	45	270	300	345		9.74	53	11.6	70.0	1.27	10
147	39	294	462	498		10.81	70	2.8	65.1	0.62	22
138	33	237	258	279		10.19	61	5.1	67.2	0.58	18
120	28	204	296	357		9.78	60	1.2	66.5	0.69	4
117	33	183	222	246		9.87	54	5.0	69.2	0.69	27
114	36	159	183	225		9.61	51	9.8	70.7	1.26	15
111	28	180	186	222		13.26	68	1.3	72.0	1.40	4
105	33	120	174	174		6.90	32	11.1	76.2	1.28	10
102	36	162	180	216		8.17	40	8.0	73.4	0.91	8
96	30	150	168	207		9.30	38	11.5	79.1	1.04	11
81	30	147	153	204		8.68	41	6.4	74.4	0.74	15
78	15	150	159	174		10.45	62	7.0	67.3	0.85	16
48	24	75	120	138		10.31	50	7.5	74.2	0.94	18
27	12	27	30	30		11.62	58	3.5	73.0	1.36	10
Means..	103	30	168	206	237	9.91	53	6.56	71.3	29.97	13.4

Table XV.
Results for October—November, 1895, forenoon, about 10.30 A.M.

Volts observed at stations						Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	E	F							
830	115	1452	1785	2362		7.08	97	0	42.8	1.42	5
603	110	1160	1323	2000		4.02	77	0.5	34.2	0.75	5
341	75	588	951	1540		4.75	83	0	36.4	0.55	3
296	42	653	893	1420		4.41	75	1.7	37.0	1.13	6
290	72	652	879	1456		5.85	93	0	39.0	1.52	0
278	49	493	725	1058		6.28	75	2.2	47.2	1.47	11
183	30	247	391	638		7.81	87	0.1	49.0	0.88	10
174	52	296	449	783		5.35	79	0	41.0	0.57	13
168	26	278	391	638		8.16	93	0	48.1	1.38	0
162	44	464	580	615		4.65	75	1.3	38.8	0.51	8
110	32	226	302	806		9.07	76	1.2	57.0	0.73	29
90	12	200	426	751		4.81	87	0	35.4	0.81	8
30	12	53	110	133		7.11	77	0.4	49.3	1.16	18
Means..	273	52	520	708	1092	6.10	83	0.57	42.7	29.99	8.9

Table XVI.
Results for October—November, 1895, afternoon, about 4.30 P.M.

Volts observed at stations						Vapour, grams per cubic metre.	Relative humidity.	Hours of sunshine.	Temperature, Fahrenheit.	Barometer, 29 inches +	Wind velocity, miles per hour.
A	B	C	E	F							
458	104	1027	1227	2053		7.00	72	1.6	51.0	1.46	7
319	64	580	870	1433		7.90	89	0.1	48.5	0.96	5
247	50	328	516	826		5.40	80	5.2	41.0	0.71	6
215	55	435	595	879		5.26	71	7.4	43.7	0.50	4
197	52	377	638	971		5.38	74	0	42.7	0.54	14
194	35	363	458	719		5.85	75	7.6	49.0	1.47	8
180	39	397	568	957		5.72	62	3.1	49.7	1.25	9
174	15	290	515	597		7.76	86	3.0	49.0	1.42	7
157	46	322	537	986		4.90	69	3.4	42.7	1.05	7
29	12	52	93	122		5.58	75	4.4	43.5	0.48	8
Means..	217	47	418	602	954	6.17	75	3.58	46.1	29.98	7.5

chronological, but in descending order of the voltages observed at station A. In all the tables the humidity of saturation is taken as 100.

§ 21. I have divided the results in each of the previous eight tables into two groups, according to the order of voltages at station A. The two groups are equal in number of constituents, except as regards Table XV, where, following a marked line separating the voltages, I have included six in the first group, and seven in the second; and Table X, where I have included four in the first group, and three in the second. In the last-mentioned case, the best line of demarcation is doubtful, and, on account of this, and the small number of constituents, little weight can be attached to the results.

It may seem arbitrary to determine the groups by reference to station A exclusively. It is, however, the station least influenced by buildings, and best fitted for accurate readings, while B is the worst. Also it will be seen that if one had adopted either C, D, or E as the standard station, or had taken a mean from all the stations, whilst the order of the constituents would in some tables have been considerably affected, the groups themselves would have suffered little or no change.

Table XVII gives the mean potentials at station A for each group in the several series of observations, with the corresponding mean values of the meteorological elements.

Table XVII.

Series of observa- tions.	Time.	Potential at Station A.		Vapour, grams per metre.		Relative humidity.		Hours of sunshine.		Temperature, Fahrenheit.		Barometer, 29 inches +		Wind velocity, miles per hour.	
		1st n.	2nd n.	1st n.	2nd n.	1st n.	2nd n.	1st n.	2nd n.	1st n.	2nd n.	1st n.	2nd n.	1st n.	2nd n.
I {	Forenoon...	204	124	6.57	5.87	89	76	0.37	1.36	42.8	44.3	1.11	0.94	9.3	17.0
	Afternoon..	166	109	6.02	5.91	83	87	0.90	0.17	42.8	41.0	0.81	1.25	10.0	7.7
II {	Forenoon...	342	117	6.35	6.93	79	76	0.68	1.37	45.6	49.3	0.95	0.74	6.9	14.8
	Afternoon..	237	124	6.31	6.93	66	70	3.82	3.26	50.7	51.7	0.85	0.68	11.9	15.4
III {	Forenoon...	120	83	9.90	9.06	59	56	2.15	3.17	67.2	66.1	1.12	0.92	6.8	12.4
	Afternoon..	130	77	10.47	9.35	60	46	5.26	7.86	68.7	73.9	0.93	1.02	14.3	12.6
IV {	Forenoon...	440	131	5.40	6.71	83	82	0.73	0.43	39.6	45.5	1.14	0.86	5.0	12.3
	Afternoon..	287	147	6.19	6.16	77	73	2.86	4.30	45.4	46.8	0.83	1.13	7.2	7.8

§ 22. A discussion might be based on the previous nine tables alone. Partly, however, to satisfy those who prefer a grouping system like that of Exner, I add further tables, in which the observations are arranged in groups, according to the magnitude of some one meteorological element. In dealing with vapour density, barometric pressure and wind velocity, separating lines have been drawn at fixed values of the element considered. In the case of vapour density the limits required to be altered with the season. In the case of barometric pressure and wind velocity it was deemed sufficient to draw only one separating line, which answered, it will be seen, very nearly to the mean value. In dealing with sunshine and temperature,* the division has been into equal, or as nearly equal, groups as possible. After the tables follows a discussion, which embraces Tables IX to XVII as well.

Table XVIII.

Arrangement according to Vapour Density.

Series of observations.	Vapour grams per metre.	Forenoon.			Afternoon.		
		Number of observations.	Mean vapour density.	Mean potential at A.	Number of observations.	Mean vapour density.	Mean potential at A.
I {	> 6	7	7·71	191	4	6·61	141
	< 6	11	5·27	147	3	5·13	143
II {	> 7	8	8·12	185	6	8·35	140
	7 to 6	8	6·39	170	6	6·45	168
	< 6	8	5·40	333	8	5·46	219
III {	> 10	4	12·30	104	6	11·11	92
	10 to 9	4	9·39	117	5	9·66	122
	< 9	8	8·12	93	3	7·92	96
IV {	> 6	6	7·58	266	4	7·38	286
	< 6	7	4·83	279	6	5·37	171

* The $n + 1$ th constituent in the forenoon observation of Series IV is omitted, as it was doubtful whether to group it with the first n or last n .

Table XIX.

Arrangement according to Hours of Sunshine.

Series of observations.	Sunshine.	Forenoon.			Afternoon.		
		Num ber of obser- vations.	Mean sunshine hours.	Mean potential at A.	Number of obser- vations.	Mean sunshine hours.	Mean potential at A.
I {	Most	8	1·94	158	4	1·03	154
	Least	10	0	169	3	0	124
II {	Most	12	1·90	256	10	6·09	151
	Least	12	0·14	203	10	0·99	209
III {	Most	8	4·62	93	7	9·50	101
	Least	8	0·70	111	7	3·61	106
IV {	Most	7	1·06	237	5	5·60	168
	Least	6	0	315	5	1·56	266

Table XX.

Arrangement according to Temperature.

Series of obser- vations.	Tempera- ture.	Forenoon.			Afternoon.		
		Number of obser- vations.	Mean tempera- ture.	Mean potential at A.	Number of obser- vations.	Mean tempera- ture.	Mean potential at A.
I {	Highest	9	47·2	170	4	45·7	154
	Lowest	9	39·9	159	3	37·1	124
II {	Highest	12	51·4	191	10	56·1	145
	Lowest	12	43·5	267	10	46·4	216
III {	Highest	8	69·6	95	7	74·6	81
	Lowest	8	63·6	109	7	68·0	125
IV {	Highest	6	48·9	266	5	49·4	265
	Lowest	6	36·8	297	5	42·7	169

Table XXI.

Arrangement according to Barometric Pressure.

Series of observation.	Barometric pressure, in inches.	Forenoon.			Afternoon.		
		Number of observations.	Mean pressure.	Mean potential at A.	Number of observations.	Mean pressure.	Mean potential at A.
I {	> 30	12	30·20	178	4	30·21	119
	< 30	6	29·69	136	3	29·71	172
II {	> 30	9	30·20	279	6	30·20	184
	< 30	15	29·64	199	14	29·58	179
III {	> 30	8	30·23	108	6	30·27	103
	< 30	8	29·81	96	8	29·75	104
IV {	> 30	6	30·35	315	5	30·33	233
	< 30	7	29·69	238	5	29·64	201
All combined {	> 30	35	30·23	212	21	30·25	160
	< 30	36	29·69	173	30	29·65	162

Table XXII.

Arrangement according to Wind Velocity.

Series of observations.	Wind velocity, miles per hour.	Forenoon.			Afternoon.		
		Number of observations.	Mean velocity.	Mean potential.	Number of observations.	Mean velocity.	Mean potential.
I {	10 or > 10	13	16·6	174	3	16·7	142
	< 10	5	4·2	140	4	3·2	141
II {	10 or > 10	11	17·7	159	13	17·8	179
	< 10	13	5·1	289	7	5·9	183
III {	10 or > 10	6	15·0	85	11	15·6	101
	< 10	10	6·3	112	3	5·3	111
IV {	10 or > 10	5	16·2	155	1	14·0	197
	< 10	8	4·4	347	9	6·8	219
All combined {	10 or > 10	35	16·6	151	28	16·7	145
	< 10	36	5·1	232	23	5·7	180

Vapour Density.

§ 23. In Tables XVII and XVIII the forenoon observations of series IV, and both forenoon and afternoon observations of series II, support Exner's theory to a certain extent, inasmuch as they decidedly, on the whole, associate higher potential with lower vapour density. The forenoon observations, however, of series I lead in both tables to exactly the opposite result. Also in Table XVII, in five cases out of eight, the higher potential is associated with the higher vapour density. In some instances, *e.g.*, the afternoon observations of series III and IV, Tables XVII and XVIII lead to diametrically opposite conclusions. The following are instances of corresponding *means* of vapour density and potential, culled from the several tables. In Table XVIII, 8.12 occurs with both 185 and 93; in Table XI, 6.64 with 229; in Table XII, 6.62 with 180; in Table XVII, 6.57 with 204, 6.35 with 342, and 6.31 with 237; in Table XVIII, 6.61 with 141, 6.45 with 168, and 6.39 with 170. Again, in Tables XV and XVI we find 6.10 associated with 273, and 6.17 with 217. Lastly, in Table XVIII we have the following combinations, 5.46 with 219, 5.40 with 333, 5.37 with 171, and 5.27 with 147.

In the face of such results, it seems difficult to believe in any intimate and uniform connexion whatsoever between potential gradient and vapour density.

Relative Humidity.

§ 24. No special table is devoted to this. In Table XVII no less than six sub-cases out of eight associate higher relative humidity with higher potential. It will be noticed, however, that in three out of the six sub-cases referred to the differences between the mean humidities answering to the two groups are smaller than in either of the two sub-cases which associate higher relative humidity with lower potential. With the exception of the forenoon observations of series I, and the afternoon observations of series III, the differences between the mean relative humidities in the two groups are very small. Thus, on the whole, the evidence in favour of any distinct association of higher relative humidity and higher potential is insufficient.

Sunshine.

§ 25. There is in both the Tables XVII and XIX a balance of evidence in favour of a connexion of low potential with long previous sunshine. Out of eight sub-cases in each table, five favour this connexion in Table XVII, and six in Table XIX. The only sub-case in which the tables agree in associating higher potential with longer previous sunshine is the afternoon observations of series I, and, for

reasons already mentioned, this is not an important exception. There is thus a certain amount of general support to Elster and Geitel's theory. An examination, however, of numerical details does not seem favourable to any such intimate connexion between sunshine and potential, as the formula suggested by them would imply.

Taking, for instance, Table XIX, we notice in series III that, in the afternoon, a mean potential of 106, answering to a mean of 3·6 hours' sunshine, falls only to 101 when the hours of sunshine rise to 9·5. Again, in the forenoon observations of the same series, the mean hours of previous sunshine increase fully six times, while the potential falls only from 111 to 93.

The afternoon observations of series II are a striking illustration of the diverse conclusions to which the different methods adopted in Tables XVII and XIX may lead.

Temperature.

§ 26. The forenoon observations of series IV, and both forenoon and afternoon observations of series II associate high potential with low temperature in both Tables XVII and XX; and the balance of evidence is unquestionably in this direction. The only sub-case in which the two tables agree in associating higher potential with higher temperature is the afternoon observations of series I, which, as already explained, is the least important of the eight instances.

On the whole, the evidence in favour of a connexion of high potential with low temperature is just about as strong as that in favour of a connexion of high potential with little previous sunshine.

Barometric Pressure.

§ 27. Higher potential is associated with higher pressure in the forenoon observations of each of the four series both in Tables XVII and XXI. In the afternoon observations, however, the higher potential is associated with the lower pressure in three cases out of four in Table XVII, and in two cases out of four in Table XXI. The phenomenon, in short, is an apparently clear association of high potential and high barometric pressure in the forenoon, and an apparent absence of any connexion in the afternoon.

Wind Velocity.

§ 28. A somewhat striking similarity exists here to the phenomena observed in the case of barometric pressure.

In both the Tables XVII and XXII there is in the forenoon results a conspicuous association of high potential with low wind velocity. In Table XXII, it is true, series I observations form an exception,

but it is rather apparent than real. For if, instead of ten, we adopt eleven miles an hour as limiting value for the velocity, we get in that instance two equal groups with the following results :—

Group.	Mean velocity.	Mean potential.
1st	19·6	153
2nd	6·8	175

Higher potential is here associated with lower velocity, and, as the groups are equal, the result is presumably a fairer representation of the facts than that afforded by Table XXII.

Whilst the association of high potential with low wind velocity in the forenoon seems thus conspicuous, there is in the afternoon no certain evidence of any such connexion. Thus, in Table XVII, higher potential is associated as often with higher as with lower velocity; and in Table XXII, whilst higher potential is associated with lower velocity in three sub-cases out of four, the differences between the mean potentials for the first and second groups are small. In series III observations the difference is also very uncertain. If, for instance, we divide these observations into two equal groups, by taking 15 as separating value for the velocity, we obtain for each group identically the same mean voltage, 103, though the mean velocities for the two groups are respectively 18·7 and 8·1.

In Table XXII the figures obtained by combining all four series of observations, afford an excellent example of what may happen when results, from all seasons of the year, are treated promiscuously. The individual series, as we have seen, show no clear association of high potential with low velocity in the afternoon observations, but, when the four series are combined, such an association seems conspicuous. The phenomenon, in reality, is mainly due to the comparatively large number of instances in which the velocity happened to be high during the season when the potential was at its minimum.

General Summary of bearing of Results on Theory.

§ 29. A comparatively small number of observations may be sufficient to disclose defects in an existing physical theory, and yet be inadequate to warrant the promulgation of a positive opinion as to the true theory. This is the most satisfactory point of view from which to regard the facts presented here. They are, in my opinion, sufficient to show the incompleteness of any theory which assumes simultaneous values of potential and any single meteorological element to be so intimately connected that the value of the one can be deduced, as a rule, from that of the other without taking into account other important influences. On the other hand, they are not sufficiently varied to justify the conclusion that the connexions

traced in §§ 25 to 28 between low potential and long previous sunshine, high temperature, low barometric pressure, and high wind velocity constitute the normal state of matters at every station, irrespective of the hour or the season. Provisionally I should prefer to regard these associations as possibly accidental, even at Kew, but believe they indicate the lines on which more exhaustive inquiries might profitably proceed.

Another possibility indicated by these associations, viz., that the potential tends to be higher during anticyclonic than during cyclonic weather seems also worthy of attention. An attempt was indeed made in the present instance to check this conclusion directly by reference to the weather reports of the Meteorological Office. The published data relate, however, to 8 A.M. and 6 P.M.; so that, on a considerable number of occasions the nature of the isobars at the hours of the observations was uncertain. Taking the remaining instances, I calculated the mean potential for the cyclonic and anticyclonic conditions separately for each one of the four series, treating the forenoon and afternoon observations apart, except in the case of the first series. In five cases out of the seven thus presented, the mean potential for the anticyclonic group exceeded that for the cyclonic. There is thus something to be said for the hypothesis. It should be mentioned, however, that individual occurrences of high potential in cyclonic weather and of low potential in anticyclonic weather were not infrequent.

§ 30. The results of the present inquiry are, I believe, irreconcilable with Exner's theory, in so far as it connects simultaneous *individual* values of potential and vapour density. The question remains open whether the annual variations of potential and vapour density may not be related through a formula of Exner's type—

$$dV/dn = A/(1+Bq_0),$$

where A and B are constants for a given station, dV/dn and q_0 representing monthly means of potential gradient and vapour density near the ground.

Whilst the data available are far too limited for drawing a final conclusion, I think it worth while to add in Table XXIII a comparison of the results at station A—regarded as 60 inches above the ground—with those deduced from Elster and Geitel's special form of the equation

$$dV/dn = 1410/(1+1.15q_0).$$

The figures are the arithmetic means of the values for the forenoon and the afternoon hours of observation.

Table XXIII.

Series of observations.	Potential at Station A.	
	Observed.	Calculated.
I.	153	269
II.	205	249
III.	103	176
IV.	245	267

The density of aqueous vapour is a quantity having but a small diurnal variation,* and it would appear, from a table published by General Sabine† that the calculated mean potential for the day—taken as the mean of the calculated values for the 24 hours—would differ but little from that answering to only the two times, 10.30 A.M. and 4.30 P.M. Thus the calculated values in Table XXIII may be regarded as close approximations to the true calculated means for the seasons of the four observations. On the other hand, according to the table of diurnal variation of potential in the paper by Mr. Whipple already referred to, the true means obtained from observations at every hour of the day might be expected to be on an average some 10 per cent. higher than the observed values in Table XXIII. It ought, further, to be remembered that, as explained in § 4, the potential at station A must fall short of the true potential at a point 60 inches above the ground in the open, also the fraction of the existing potential picked up by the portable electrometer may be appreciably less than unity. Thus the fact that the calculated values in Table XXIII are so decidedly larger on the average than the observed is perhaps rather in favour of the formula than otherwise.

If we may judge, however, from the few data in the table, there seems some ground for the suspicion that the formula will prove to give too narrow a range.

Before concluding, I have much pleasure in acknowledging the ready and valuable help I have received from Mr. E. G. Constable, Senior Assistant at the Kew Observatory. Mr. Constable took all the electrical observations and the measurements of the meteorological curves, and gave me in addition much useful information derived from his long experience of the working of the electrograph and portable electrometer.

* A fact difficult to reconcile with the general form of Exner's theory.

† 'Roy. Soc. Proc.,' vol. 18, 1869, p. 8.